TESTING OF A CUMMINS B5.9-195 LPG ENGINE

FINAL REPORT

SwRI Project No. 03-2369

Prepared for:

**The ADEPT Group, Inc.
1575 Westwood Boulevard, Suite 200
Los Angeles, CA 90024**

February 1999

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO
DETROIT
HOUSTON
WASHINGTON, DC

TESTING OF A CUMMINS B5.9-195LPG ENGINE

FINAL REPORT

SwRI Project No. 03-2369

Prepared for:

The ADEPT GROUP, Inc.
1575 Westwood Boulevard, Suite 200
Los Angeles, California 90024

Prepared by:

David M. Meyers

February, 1999

Approved:

Daniel W. Dickey, Director
Department of Engine Research

EXECUTIVE SUMMARY

This report summarizes the results of running two LPG fuel blends on a Cummins B5.9-LPG engine. The engine was operated at various speeds and loads with the two fuel blends to determine if there was any significant impact on engine performance, specifically detonation and misfire. The fuels tested consisted of "Cert. Fuel" (HD-5) and an LPG blend high in propylene.

The engine was instrumented for both low-speed data (temperatures, pressures, speed, torque, fuel flow, etc) and high-speed data (cylinder pressure) as well as emissions. The engine was treated as a black box (i.e. no modifications were done to compensate for varying conditions). Emissions were measured to monitor the air-fuel ratio at each test condition. Brake specific emissions are not presented since the engine was not equipped with an oxidation catalyst; thus results will differ from published values.

In general, engine performance was unaffected by fuel blend. The engine was able to produce full power at each engine speed with both blends of fuel. No detonation was encountered (audibly or visually with an oscilloscope) with either fuel blend.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

This report discusses the results of running two LPG fuel blends on a Cummins B5.9-195 LPG Engine. The engine was operated at various speeds and loads with the two fuel blends to determine if there was any significant impact on engine performance, specifically detonation and misfire. The fuels tested consist of a "Cert. Fuel" (Fuel A) and a blend high in propylene (Fuel B). Table 1.1 shows the target fuel composition for the two fuel blends. Appendix A-1 contains the actual composition for each of the six bottles of Fuel A. Appendix A-2 contains the actual composition for each of the six bottles of Fuel B.

Table 1.1 – Target Fuel Specification

	Fuel A	Fuel B
Propane (volume %)	94.3	85.0
Propylene (volume %)	3.8	10.0
Butane (volume %)	1.9	5.0

The engine was instrumented for both low-speed data (temperatures, pressures, speed, torque, fuel flow, etc) and high-speed data (cylinder pressure). The engine was treated as a black box (i.e. no modifications were done to compensate for varying conditions).

2.0 OBJECTIVES

The objective of this project was to evaluate the impact of LPG fuel composition on the steady-state performance of a Cummins B5.9 LPG engine. This objective was achieved by operating the engine with two different fuel blends over four different engine speeds (2800, 2600, 1640, and 1460 rpm) and at four different engine loads (100%, 75%, 50%, and 25%) for each speed. Engine parameters that were evaluated consisted of: torque, power, brake thermal efficiency, average peak in-cylinder pressure, average peak pressure location, indicated mean effective pressure (IMEP), COV of IMEP, ten percent burn angle, combustion duration, maximum rate of pressure rise, and cumulative heat release.

3.0 TEST CELL SETUP

3.1 Engine Installation and Test Cell Setup

The installation of a Cummins B5.9-195 LPG Engine (s/n 45738595) was initiated during the week of November 9, 1998, in the Engine and Vehicle Research Division, Department of Engine Research, Test Cell No. 4 of the Automotive Research Laboratory (Bldg. 69). The engine was purchased new by the ADEPT Group from a California Cummins Dealership. However, work on the engine installation was delayed due to the lack of some essential engine hardware, including an industrial engine flywheel, a starter motor, and an alternator. These components were necessary to complete the mounting of the engine on the test stand and alignment with the test cell dynamometer. The required parts were ordered through the local Cummins dealership, Cummins Southern Plains, after an effort to locate comparable spare parts, either in stock at the dealer or at SwRI, turned up only a starter motor. Work on the engine installation and test cell instrumentation was therefore limited until these components were procured.

Other critical engine systems that were either not provided or incomplete with the engine included the engine boost air cooling circuit. Typically an air-to-air system is used for this engine application, however, a water-cooled heat exchanger (laboratory equipment) was used in place of the air-to-air system since a cooling fan was not provided on the engine. Upon receipt of the engine flywheel and alternator (on November 19, 1998), it was determined that a special flywheel adapter plate, different from any adapters previously used on "B-series" engines at SwRI, was required to couple the new flywheel to the test stand drive shaft. This new adapter plate, which was required before the final engine test stand placement could be determined, was fabricated by SwRI personnel and installed on the engine along with the new flywheel and alternator.

The completion of the engine instrumentation was also delayed due to the removal of the cylinder head for the installation of a pressure transducer to monitor cylinder pressure and analyze high-speed combustion data. This task required some minor design work to produce an instrumented cylinder head with detailed drawings to document the placement of the pressure transducer. A Kistler type 6061B, water-cooled pressure transducer was selected for this application, which incorporated a flush-mount type installation in Cylinder No. 6 of the engine (see drawings in Appendix B). Also, during the machining of the cylinder head, the exhaust ports were drilled and tapped near the outlet flanges to allow for the installation of thermocouples to monitor individual cylinder exhaust temperatures. These cylinder head modifications were completed (November, 30, 1998) and an upper cylinder head gasket set was procured, from the local Cummins dealer, for the re-installation of the cylinder head and associated components on the engine.

After the modified cylinder head was reinstalled on the engine and with the new alternator in place, it was determined that the drive belt supplied with the engine was too large for the pulley configuration on this engine. Therefore, another belt had to be ordered from the local Cummins Dealer based on the estimated size required for the current pulley configuration.

Table 3-1. Physical Variables Measured

Physical Variable Measured	Measurement Device	Accuracy
Engine torque	Load cell	± 1% of full scale
Engine speed	Magnetic pick-up	± 0.1% of full scale
LPG flow	Mass flow meter	± 0.5% of reading
Air flow	1000 SCFM Laminar flow element (LFE)	± 2% of reading
LFE delta pressure	Pressure transducer	0.25% of full scale
LFE filter delta pressure	Pressure transducer	0.5% of full scale
LFE inlet/compressor inlet air temperature	K-type thermocouple	± 2.16°F
Compressor outlet/Intercooler inlet air temperature	K-type thermocouple	± 2.16°F
Intercooler outlet air temperature	K-type thermocouple	± 2.16°F
Manifold air temperature	K-type thermocouple	± 2.16°F
Engine coolant inlet temperature	K-type thermocouple	± 2.16°F
Engine coolant outlet temperature	K-type thermocouple	± 2.16°F
Exhaust port temperatures (6)	K-type thermocouple	± 2.16°F
Turbine outlet temperature	K-type thermocouple	± 2.16°F
LPG inlet temperature	K-type termocouple	± 2.16°F
Oil sump temperature	K-type termocouple	± 2.16°F
Ambient atmospheric humidity/temperature	Relative humidity sensor	± 2% relative humidity
Ambient atmospheric pressure	Barometer	0.025% of reading
Inlet air restriction	Pressure transducer	0.5% of full scale
Compressor outlet/intercooler inlet pressure	Pressure transducer	0.5% of full scle
Intercooler outlet/air pressure Upstream of throttle	Pressure transducer	0.5% of full scale
Manifold air pressure	Pressure transduce	0.5% of full scale
Oil gallery pressure	Pressure transducer	0.5% of full scale
LPG pessure	Pressure transducer	0.5% of full scale
Exhaust back pressure	Pressure transducer	0.5% of full scale
Turbine inlet pressure	Pressure transducer	0.5% of full scale
Cylinder pressure	Kistler 6061B pressure transducer	1% of full scale
Engine out emissions	Milton-Roy emissions bench (NO_x, CO, CO_2, O_2, and unburned HC)	2% of Reading
Blowby	J-Tec flowmaster	Reference only (comparative purposes)

Also, to complete the engine test stand setup, plumbing of the engine intake and boost air circuits, the engine exhaust system, and the engine cooling circuit was required. The engine cooling circuit was filled with a suitable coolant mixture and the original engine oil (oil in the engine when received) was put back in to the engine for the initial startup and test stand "shakedown". The test cell instrumentation and equipment calibration was conducted once all the instrumentation had been installed on the engine (see Instrumentation List in Table 3-1). The computer data acquisition system (DAQ) was customized to handle both the high-speed and low-speed data acquisition. A constant source power supply was installed to provide 13.8 VDC to the engine control unit (ECU).

The LPG fuel system was constructed starting with the placement of a 1000-gallon fuel storage tank on November 30, 1998. The plumbing for the fuel system, from the storage tank to the test cell, was completed along with the installation of a fuel flow meter, Micromotion Model CMF 025, at the engine test stand for measuring LPG flow rates. The baseline LPG (HD-5) fuel, for running the engine checkout and break-in, was delivered by Bell Hydrogas on December 10, 1998. The installation of a Cummins B5.9-195 LPG Engine was completed (the week of December 7, 1998) and prepared for the "shakedown" of the test cell setup and the start of the break-in.

3.2 Initial Engine Startup and Break-in

An initial engine checkout and test cell "shakedown" was conducted during the week of December 14, 1998. The power was low initially (approx. 112 kW), but was determined to be caused by a lack of adequate exhaust back pressure on the exhaust system. A maximum exhaust back pressure of 13.6 kPa was set at rated speed, full load. After the engine performance was confirmed and the initial data were reviewed, the 50-Hour Break-in was started on December 17, 1998. The power was high during the first couple of hours of Break-in. After an hour on break-in (approximately 7 engine hours), the engine was stopped to change oil. A Valvoline Premium Blue gas engine oil (GEO) was purchased from the local Cummins Dealership, Cummins Southern Plains. The break-in was resumed and completed on December 23, 1998.

4.0 TEST PROCEDURES

Upon completion of the 50-hour break in, the engine was instrumented for exhaust gas analysis and steady-state fuel comparison testing was initiated. Engine testing was conducted during the week of December 28, 1998, on both LPG test fuels (in bottles labeled HD-5 and Fuel 1) supplied by the ADEPT Group. An initial test was performed on the tank fuel (locally supplied HD-5 fuel), and then the engine was mapped using the two test fuels per the following conditions: 2800, 2600, and 1460 rpm at 25%, 50%, 75%, and 100% of full load at each speed. High-speed in-cylinder pressure data were taken and steady-state exhaust emissions measurements were recorded at each test condition. Upon completion of testing at the three aforementioned speeds, SwRI and ADEPT agreed that torque peak should also be investigated. The two fuels were then re-tested at 1640 rpm (100%, 75%, 50%, and 25% load). Table 4-1 shows the run numbers associated with each fuel and speed/load condition.

Throughout the test, manifold boost temperature was held at a maximum of 51° C, and coolant-out was held constant at 89° C ± 1° C. At each engine speed, the engine was operated at wide-open throttle to determine full load torque. The throttle was then adjusted to produce an engine output of the desired load (i.e. 75%, 50%, and 25%). This procedure was repeated for each fuel blend.

A complete set of data for Fuel A (bottles labeled HD-5) can be found in Appendix B-1. A complete set of data for Fuel B (bottles labeled Fuel 1) can be found in Appendix B-2. Low-speed data were then plotted for each fuel as a function of engine speed and load. This was done to verify that the trends being observed were correct. A complete set of low-speed data graphs for Fuel A can be found in Appendix C-1. A complete set of low-speed data graphs for Fuel B can be found in Appendix C-2.

Cylinder pressure data were recorded at each test condition. Data were recorded for 50 engine cycles at 0.5 crank angle degree intervals. Values of IMEP, peak pressure location, ignition delay angle (based on 10% burn), combustion duration (based on 10% burn to 90% burn), maximum rate of pressure rise, maximum rate of pressure rise location, bulk gas temperature, and cumulative heat release were obtained for each cycle and then averaged. A standard deviation for IMEP was determined from this data. The COV of IMEP was determined by dividing standard deviation of IMEP by the average IMEP. These data are shown for each run number in Appendices B-1 for Fuel A and B-2 for Fuel B.

Additionally, each of the cylinder pressures obtained at each crank angle were averaged to obtain an average cylinder pressure trace. IMEP, peak pressure, peak pressure location, ignition delay angle (based on 10% burn), combustion duration (based on 10% burn to 90% burn), maximum rate of pressure rise, maximum rate of pressure rise location, bulk gas temperature, and cumulative heat release were then calculated from the average cylinder pressure data. Plots of these data are contained in Appendix D-1 for Fuel A, and Appendix D-2 for Fuel B. These plots graphically depict the average cylinder pressure trace (shown in black); plus and minus one standard deviation (shown in green); the instantaneous heat release based on the average cylinder pressure trace (shown in blue); the cumulative heat release based on the average cylinder pressure trace (shown in magenta); and the bulk gas temperature based on the average cylinder pressure trace (shown in red). Also shown in these graphs are several other values obtained from the average cylinder pressure trace which are listed in the upper left-hand corner of the figure. It should be noted that the values in the box are calculated from the average cylinder pressure trace while the values shown in Appendices B1 and B2 are calculated from each individual cycle and then averaged.

Table 4-1. Test Matrix

Engine Speed	Percent Load	Actual Load	Fuel	Run Number
2800	100	134	Fuel A	116
2800	75	102	Fuel A	117
2800	50	69	Fuel A	118
2800	25	35	Fuel A	119
2600	100	145	Fuel A	120
2600	75	110	Fuel A	121
2600	50	73	Fuel A	122
2600	25	38	Fuel A	123
1640	100	100	Fuel A	150
1640	75	75	Fuel A	151
1640	50	50	Fuel A	152
1640	25	25	Fuel A	153
1460	100	87	Fuel A	124
1460	75	65	Fuel A	125
1460	50	44	Fuel A	126
1460	25	22	Fuel A	127
2800	100	130	Fuel B	128
2800	75	98	Fuel B	129
2800	50	67	Fuel B	130
2800	25	33	Fuel B	131
2600	100	143	Fuel B	132
2600	75	109	Fuel B	133
2600	50	72	Fuel B	134
2600	25	37	Fuel B	135
1640	100	101	Fuel B	145
1640	75	75	Fuel B	146
1640	50	51	Fuel B	147
1640	25	25	Fuel B	148
1460	100	88	Fuel B	136
1460	75	66	Fuel B	137
1460	50	45	Fuel B	138
1460	25	22	Fuel B	139

5.0 RESULTS

In general, engine performance was unaffected by fuel blend. The engine was able to produce full power (145 kW) at each engine speed with both blends of fuel. No detonation was encountered (audibly or visually with an oscilloscope) with either fuel blend.

Figures 5-1 through 5-6 depict the full load comparison between the two fuels for power, brake thermal efficiency, average peak cylinder pressure, IMEP, COV of IMEP, and lambda (based on exhaust composition analysis), respectively. As can be seen from these figures, only minor variations in the parameters being measured were observed between the two fuel blends under full load conditions. A full set of graphs comparing the results of the two fuels at full load conditions can be found in Appendix D-1. Similar results were observed for the other load conditions. Low-speed comparison graphs for 75, 50, and 25 percent load can be found in Appendices D2, D3, and D4, respectively.

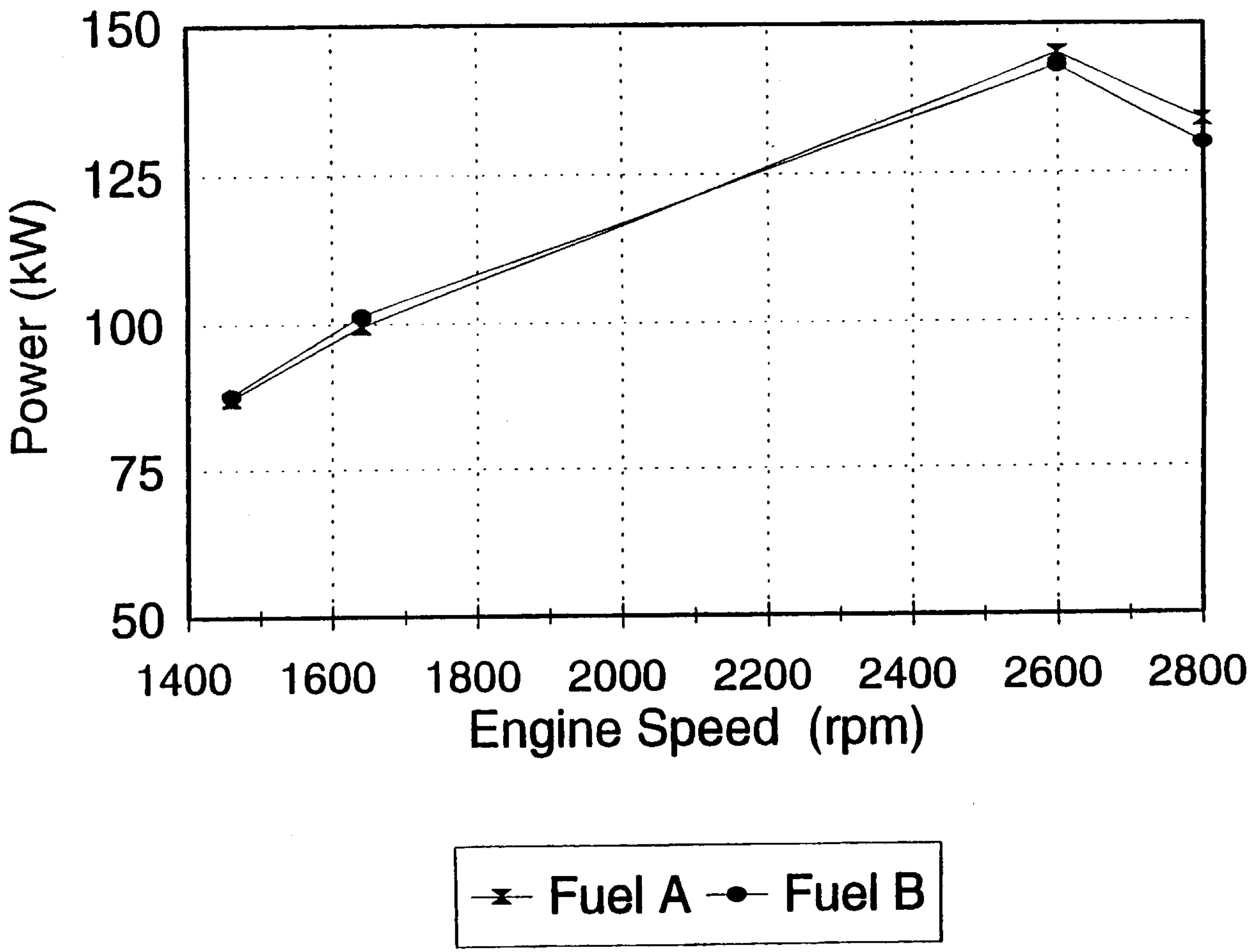

Figure 5-1. Power vs Speed Comparison at 100% Load

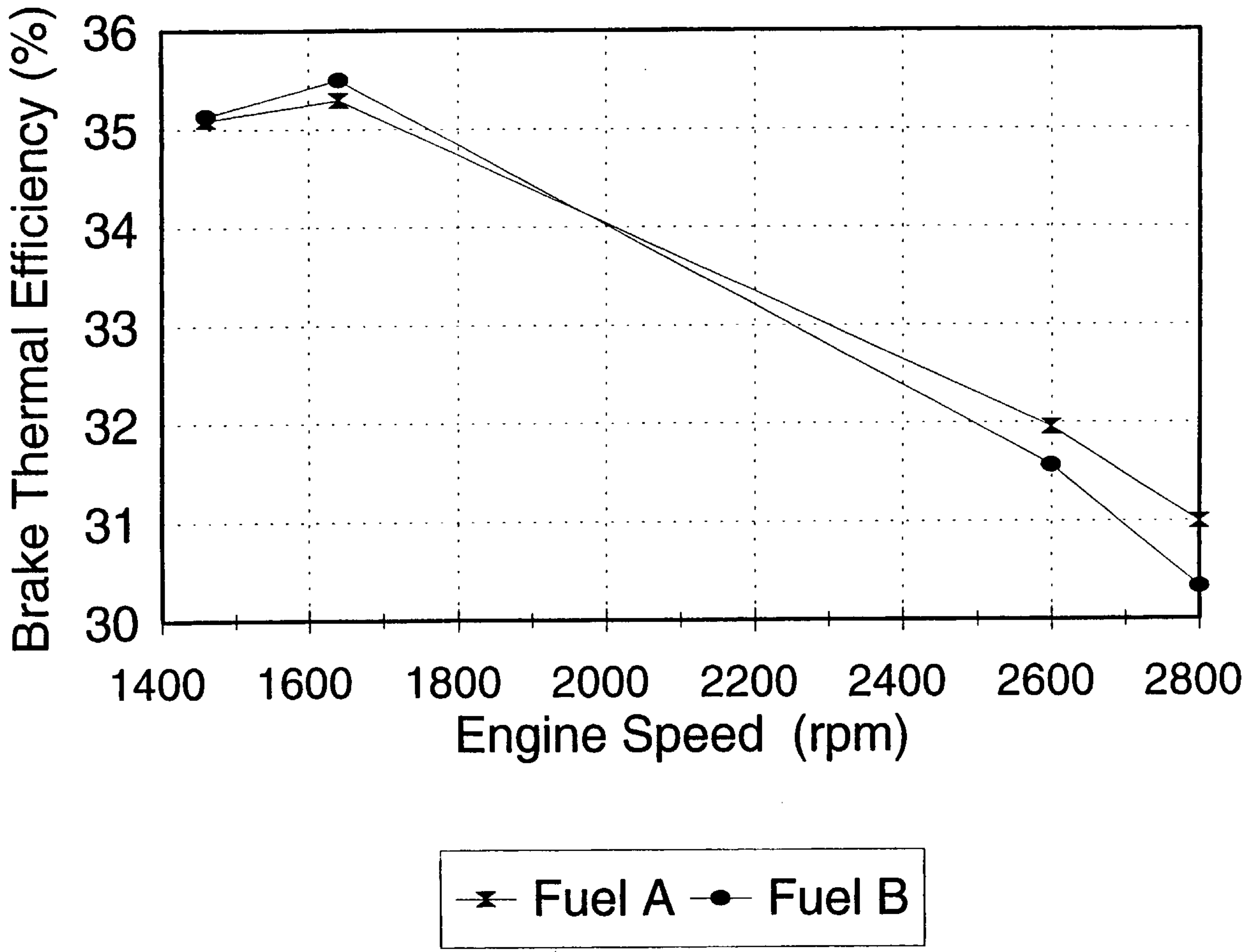

Figure 5-2. BTE vs Speed Comparison at 100% Load

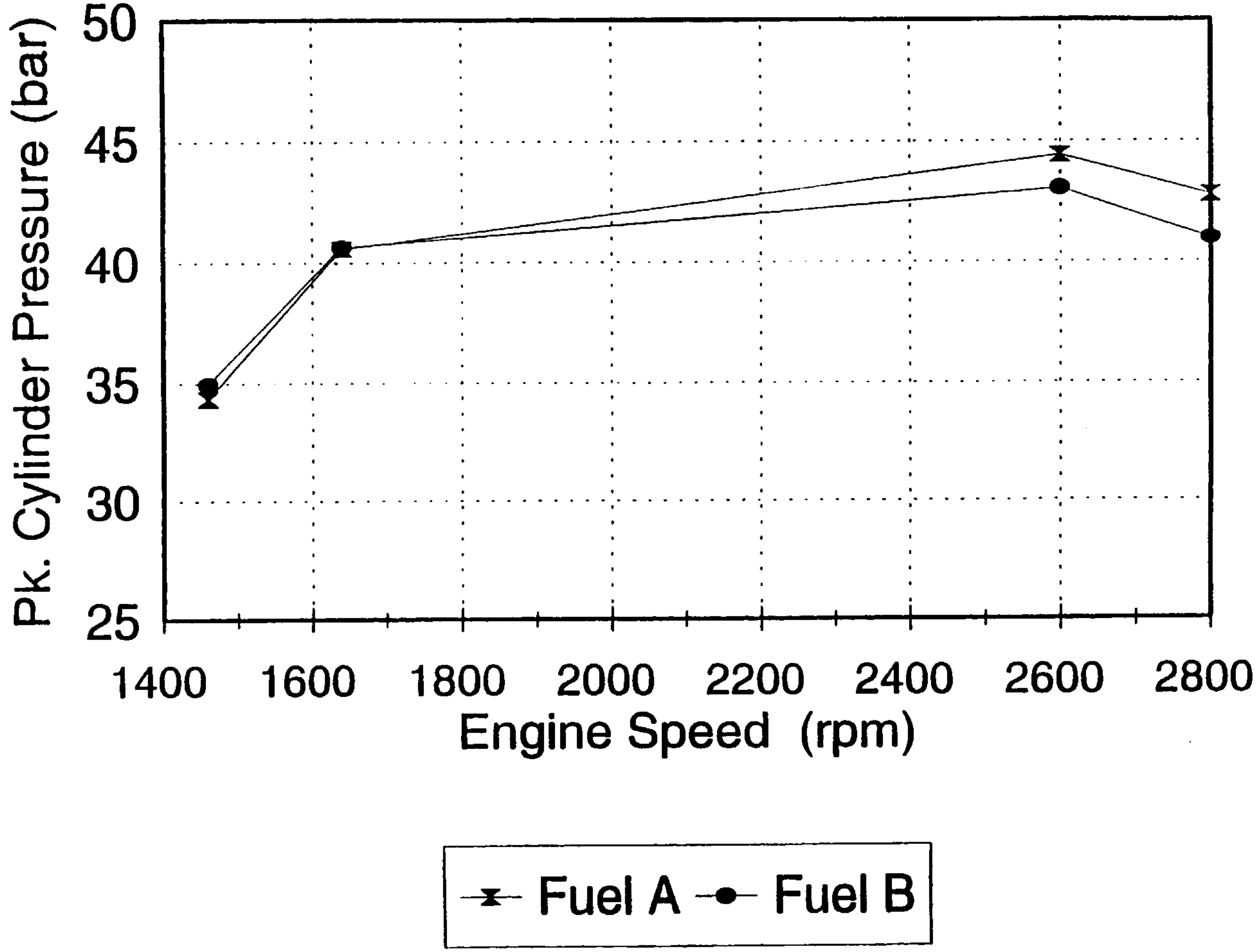

Figure 5-3. Average Peak Cylinder Pressure vs Speed Comparison at 100% Load

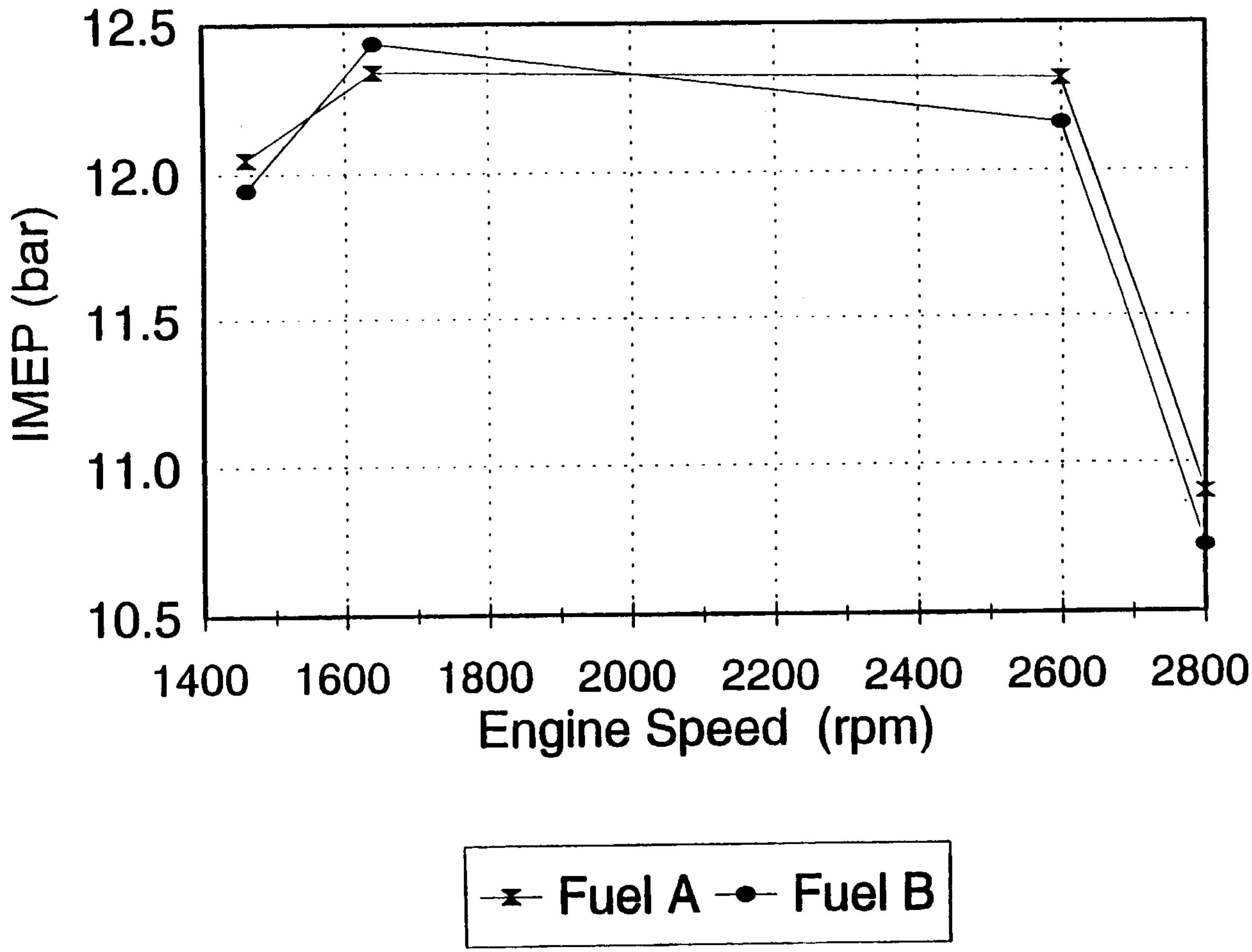

Figure 5-4. IMEP vs Speed Comparison at 100% Load

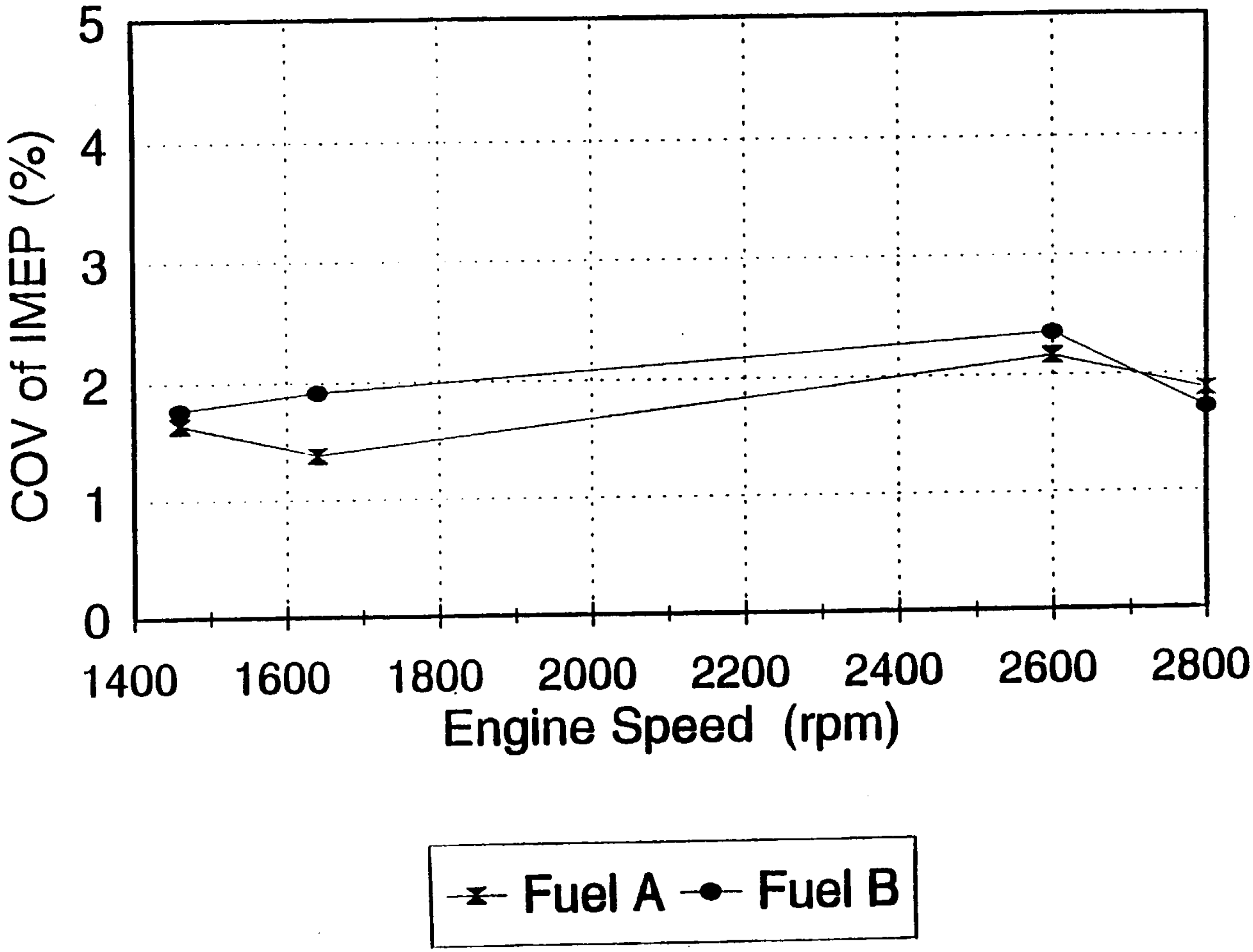

Figure 5-5. COV of IMEP vs Speed Comparison at 100% Load

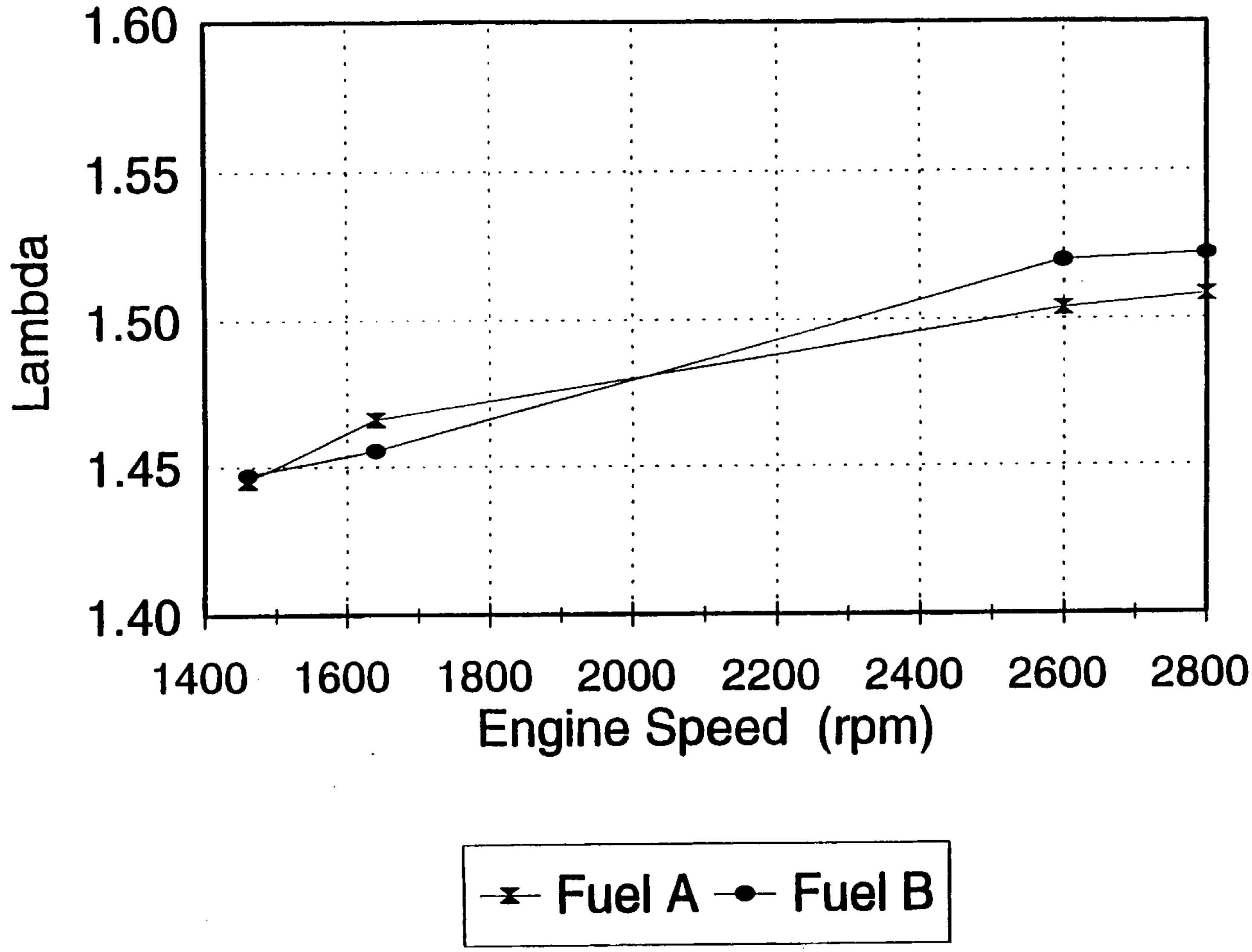

Figure 5-6. Lambda vs Speed Comparison at 100% Load

6.0 OTHER OBSERVATIONS

Some other observations that were noted during testing are summarized in the following sections:

6.1 High Power During Break-in

During the early stages of the 50-hour break-in, the engine power increased steadily. Power output was observed as high as 165 kW during the first few hours of testing. This high power output stopped after the engine was stopped and later restarted.

6.2 Low Power Fluctuations During Break-in

During the first half of the 50-hour break-in, the engine power would periodically fluctuate. Power would drop to as low as 112 kW before coming back up to rated power. Upon further investigation, it was determined that the power fluctuations corresponded to a drop in fuel supply pressure. During this period of the break-in, the tank pressure was approximately 480 kPa_g. The supply pressure to the regulator was approximately 448 kPa_g. However, occasionally the supply pressure would drop below 430 kPa_g. When this occurred, the engine would misfire and drop in power. To ensure uninterruptable completion of break-in, nitrogen was supplied to the top of the tank to maintain tank pressure at a minimum of 518 kPa_g.

6.3 Low Power Upon Start Up

One last observation that was made was the occasional occurrence of low power upon start up. In these occasions, the engine was started and warmed up to operating temperature before applying load. However, when load was applied the engine was approximately 15 kW low on power. Going up and down in speed and load would not fix the low power problem. The only thing that would fix the problem was to turn the engine off, allow the ignition to be energized for a brief period of time, and then restart the engine. When this process was performed, the engine was able to make full rated power. This occurred on several occasions and with both fuels.